AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2017GL074232

Key Points:
- The Alaskan Arctic warmed 0.71°C/decade during 1998-2015 as shown by newly collected in situ observations
- The newly estimated Alaskan Arctic warming trend is much higher than that from commonly used global gridded data sets
- The sparse in situ measurements over the Arctic may imply large uncertainties in the recently estimated global warming hiatus

Supporting Information:
- Supporting Information S1
- Data Set S1

Correspondence to:
T. Zhang,
tjzhang@lzu.edu.cn

Citation:
Wang, K., T. Zhang, X. Zhang, G. D. Clow, E. E. Jafarov, I. Overeem, V. Romanovsky, X. Peng, and B. Cao (2017), Continuously amplified warming in the Alaskan Arctic: Implications for estimating global warming hiatus, *Geophys. Res. Lett.*, *44*, doi:10.1002/2017GL074232.

Received 2 JUN 2017
Accepted 24 AUG 2017
Accepted article online 30 AUG 2017

Continuously amplified warming in the Alaskan Arctic: Implications for estimating global warming hiatus

Kang Wang[1], Tingjun Zhang[2], Xiangdong Zhang[3], Gary D. Clow[1,4], Elchin E. Jafarov[5], Irina Overeem[1], Vladimir Romanovsky[6], Xiaoqing Peng[2], and Bin Cao[2]

[1]Institute of Arctic and Alpine Research, University of Colorado Boulder, Boulder, Colorado, USA, [2]Key Laboratory of Western China's Environmental Systems (Ministry of Education), College of Earth and Environmental Sciences, Lanzhou University, Lanzhou, China, [3]International Arctic Research Center and Department of Atmospheric Sciences, University of Alaska Fairbanks, Fairbanks, Alaska, USA, [4]U.S. Geological Survey, Lakewood, Colorado, USA, [5]Los Alamos National Laboratory, Los Alamos, New Mexico, USA, [6]Permafrost Laboratory, Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska, USA

Abstract Historically, in situ measurements have been notoriously sparse over the Arctic. As a consequence, the existing gridded data of surface air temperature (SAT) may have large biases in estimating the warming trend in this region. Using data from an expanded monitoring network with 31 stations in the Alaskan Arctic, we demonstrate that the SAT has increased by 2.19°C in this region, or at a rate of 0.23°C/decade during 1921–2015. Meanwhile, we found that the SAT warmed at 0.71°C/decade over 1998–2015, which is 2 to 3 times faster than the rate established from the gridded data sets. Focusing on the "hiatus" period 1998–2012 as identified by the Intergovernmental Panel on Climate Change (IPCC) report, the SAT has increased at 0.45°C/decade, which captures more than 90% of the regional trend for 1951–2012. We suggest that sparse in situ measurements are responsible for underestimation of the SAT change in the gridded data sets. It is likely that enhanced climate warming may also have happened in the other regions of the Arctic since the late 1990s but left undetected because of incomplete observational coverage.

1. Introduction

The global warming "hiatus" may be the most controversial question in climate change study during the recent decade [*Intergovernmental Panel on Climate Change (IPCC)*, 2014; *Karl et al.*, 2015; *Roberts et al.*, 2015; *Fyfe et al.*, 2016]. Studies of the apparent climate warming hiatus inspired a suite of physical explanations for its cause, including changes in radiative forcing [*Huber and Knutti*, 2014; *Santer et al.*, 2014], ocean heat storage [*Meehl et al.*, 2014; *Douville et al.*, 2015; *Roberts et al.*, 2015], and atmospheric circulation [*England et al.*, 2014; *Trenberth et al.*, 2014]. In addition to the above physical processes, incomplete observational coverage is another critical factor that may help in explaining the observed climate warming hiatus during recent decades [*Medhaug et al.*, 2017].

Arctic regions have experienced an amplified warming during the past several decades [*Serreze et al.*, 2009; *Cohen et al.*, 2014; *Walsh*, 2014]. However, recent studies indicate that a cooling period was observed from 1998 to 2012 in Alaska as a whole, while, over the Alaskan Arctic, temperature has continued to increase but at a much lower rate of 0.20°C/decade, or about 43% of the long-term rate from 1951 to 2012 [*Bieniek et al.*, 2014]. The Arctic region has perhaps the poorest ground-based observational coverage, which may be the primary reason of the bias toward cooling in evaluating climate change at a global scale [*Cowtan and Way*, 2014a]. However, since the late 1990s, several institutions and individual scientists have continuously monitored the changing climate and environment in the Alaskan Arctic. Although these measurements are disparate and used for studies in different disciplines, surface air temperature (SAT) has been measured and recorded at more than two dozen sites.

The objective of this study is to investigate climate change and variability using data and information obtained from an expanded observational network over the Alaskan Arctic, focusing primarily on the period since the late 1990s, the so-called hiatus period. Furthermore, we will demonstrate how the added observational coverage impacts the SAT change and variability estimates through comparisons to widely used gridded data sets.

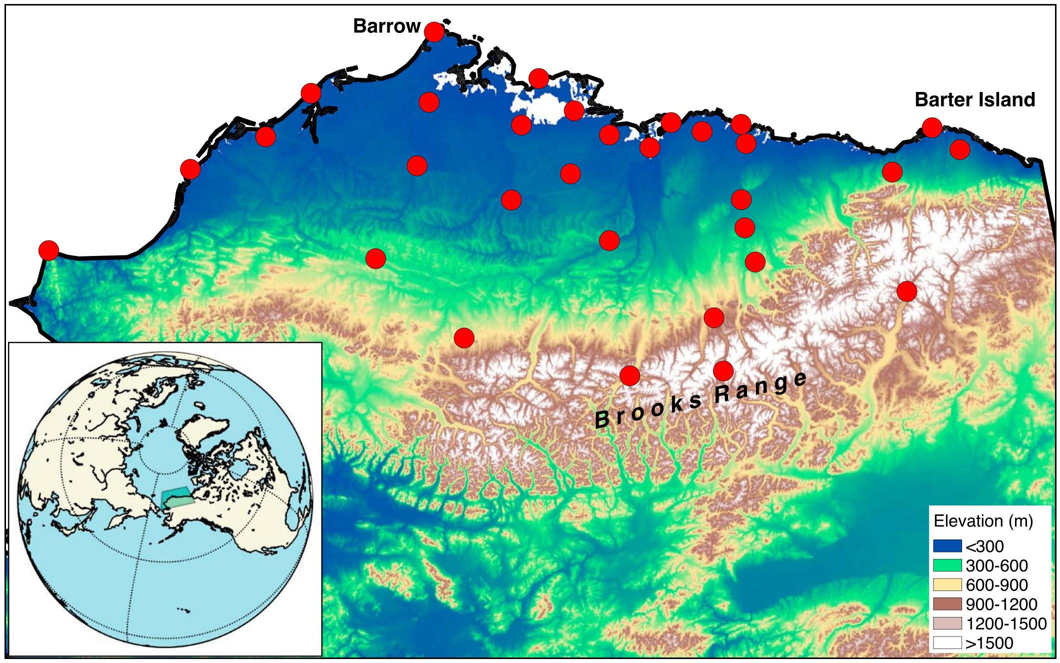

Figure 1. Climate monitoring network in the Alaskan Arctic. Red dots show the 31 stations with temperature data as obtained from GHCN, GSOD, USGS, GI-UAF, and CALM.

2. Data and Methods

2.1. Data

We collected in situ air temperature data from multiple sources, including the Global Historical Climatology Network-Daily (GHCN-Daily) [*Menne et al.*, 2012], the Global Surface Summary of the Day (GSOD), the U.S. Geological Survey (USGS) [*Urban and Clow*, 2016], the Geophysical Institute, University of Alaska Fairbanks (UAF-GI), and the Circumpolar Active Layer Monitoring (CALM) [*Brown et al.*, 2000]. A total of 31 sites (Figure 1) comprises more than twice the number of sites used in previous studies [*Bieniek et al.*, 2014] with much better spatial coverage, especially on the Arctic Coastal Plain. These supplemented sites were installed during the late 1990s, prior to the onset of the recognized hiatus period (1998–2012).

There are 11 stations in the GHCN-Daily database. Three of them (Barrow, Barter Island, and Wainwright) started measurements before 1950, and the earliest observations dated back to 1901 at Barrow. Four stations are from GSOD, and the earliest records were at Umiat which had been monitored since 1946 but closed in 2001. All of these 15 stations are operated by the National Weather Service (NWS). The USGS network has 14 automatic weather stations on the North Slope of Alaska. These were established in August 1998 with continuous measurements through the present [*Urban and Clow*, 2016]. The UAF-GI established a near-surface permafrost monitoring system mainly along the Trans-Alaskan highway during the late 1990s. In this study, we use only five stations from the UAF-GI network (because of the overlap with other data sources). The CALM network also provides data and information from five stations within the study area. We merged temperature anomalies of nearby sites (interstation distances $<$ 15 km) to avoid overrepresentation in those areas with multiple sites. The decision to merge two sites was based on the comparison of overlapping time periods. For example, there were two raw stations at Umiat (GSOD and USGS) that have 16 months of overlap with strong consistency ($R^2 > 0.99$). Thus, we were able to merge them to obtain a longer time series and avoid overrepresentation of these sites. All the measurements of SAT are compiled at a daily time scale.

The GHCN-Daily and USGS data have already been quality controlled by their host institutions. However, to ensure the robustness in our analysis, we double checked the raw collections using a series of quality control methods. We detected any outliers beyond permissible limits of correct extremes (4 standard deviations), as based on the statistical distribution. Then we checked for connectedness of values that are neighboring in time. This feature is used to reveal spasmodic errors by analyzing successive days.

For comparison, we also used three gridded climate data sets, Climate Research Unit (CRU) [*Harris et al.*, 2014], Berkeley Earth Surface Temperature (BEST) [*Rohde et al.*, 2012], and Goddard Institute for Space Studies (GISS) [*Hansen et al.*, 2010], respectively, to estimate SAT trends over the Alaskan Arctic. The CRU data set contains only three in situ stations in the Alaskan Arctic, while GISS has two stations in the region. The Berkeley Earth data set includes 43 stations with some data during the study period (Figures S1a and S1b in the supporting information), 7 stations have only less than 1 year of observations, while 9 stations have less than 5 years of data. Currently, there are 18 active Berkeley Earth stations in the Alaskan Arctic. Among these 18 active stations, 14 stations are located along the Arctic coast or within 20 km from the coast. Meanwhile, some stations are very close to each other, usually within 15 km of each other. For example, in Barrow, there were three stations within less than 10 km. These three should be merged as one in order to avoid overrepresentation of this region. After these careful considerations, there are 12 active stations in the Berkeley Earth data set with 9 of them within 20 km from the coast (Figures S1a and S1b). For GHCNv4, there were 12 active stations (Figure S1c) or 10 active stations after merging. In this study, we actually included all the active stations in the Berkeley Earth and the GHCNv4. More importantly, our data set includes 31 active stations, of which 17 stations are new and evenly distributed across the Alaskan Arctic, a much better representation of area coverage (Figure S1).

2.2. Methods

For all the in situ data, monthly mean air temperature was calculated only for those months with at least 15 days of available measurements [*Bieniek et al.*, 2014]. Mean annual air temperature (MAAT) was averaged for all years without any missing monthly mean air temperature. A major aim of this study is to determine anomalies of MAAT in the Alaskan Arctic. The World Meteorological Organization (WMO) common approach to calculate anomalies is based on a climate normal period, which is generally a 30 year period [*IPCC*, 2014]. However, there are only eight stations in our data set with a period of at least 30 years. The majority of the remaining stations were installed during the late 1990s. For this study, we calculated anomalies based on a 10 year normal period (2004–2013). Because these stations are well distributed over the Alaskan Arctic, we did not grid the station data. This might introduce a small bias when comparing to gridded products that are spatially interpolated.

We used the extent of the North Slope defined by the mapped climate divisions for Alaska [*Bieniek et al.*, 2012] to delineate our region of interest and extract gridded data from other products. The regional anomalies were averaged for all grid cells located in the region of interest by an area-weighted method [*Harris et al.*, 2014]:

$$T = \frac{\sum_{i=1}^{N} \cos\left(\mathrm{lat}_i \frac{\pi}{180}\right) \Delta T_i}{\sum_{i=1}^{N} \cos\left(\mathrm{lat}_i \frac{\pi}{180}\right)} \tag{1}$$

where N is the number of grid cells in the region, lat_i is the latitude of the grid cell i, and ΔT_i is anomaly temperature of grid cell i.

Trends were estimated by linear regression of the temperature anomalies. Statistical significance of the trend is tested by a two-tailed T test at 90% confidence level [*IPCC*, 2014; *Karl et al.*, 2015], which is represented by the p value. The uncertainty of trend is also set at the 90% confidence level [*Karl et al.*, 2015]. We used the Durbin-Watson statistic to examine the lag-1 autocorrelation. The statistics did not show statistically significant autocorrelations for 1998–2015 or 1951–2015 (p values were 0.75 and 0.24, respectively). Thus, we did not consider autocorrelation in this study.

3. Results

We constructed a new time series of MAAT anomalies which shows a warming trend of 0.23°C/decade from 1921 through 2015 (Figure 2a). This is ~20% higher than previously reported (Table 1). The low-frequency interdecadal variations show that SAT increased from the early 1920s through the early 1940s at ~0.30°C/decade. Subsequently, SAT decreased at −0.30°C/decade from the early 1940s through the mid-1970s. A steady and enhanced SAT increase of 0.78°C/decade occurred from 1976 to 2015, which is approximately 3.4 times faster than the rate over the whole period from 1921 to 2015.

Seasonally, temperature increases during the winter months (December–February (DJF)) dominated the warming trend at 0.36°C/decade during 1921–2015 (Figure 2b). In addition, an important signal we found is that only spring months (March–May (MAM)) showed a negative temperature trend during the

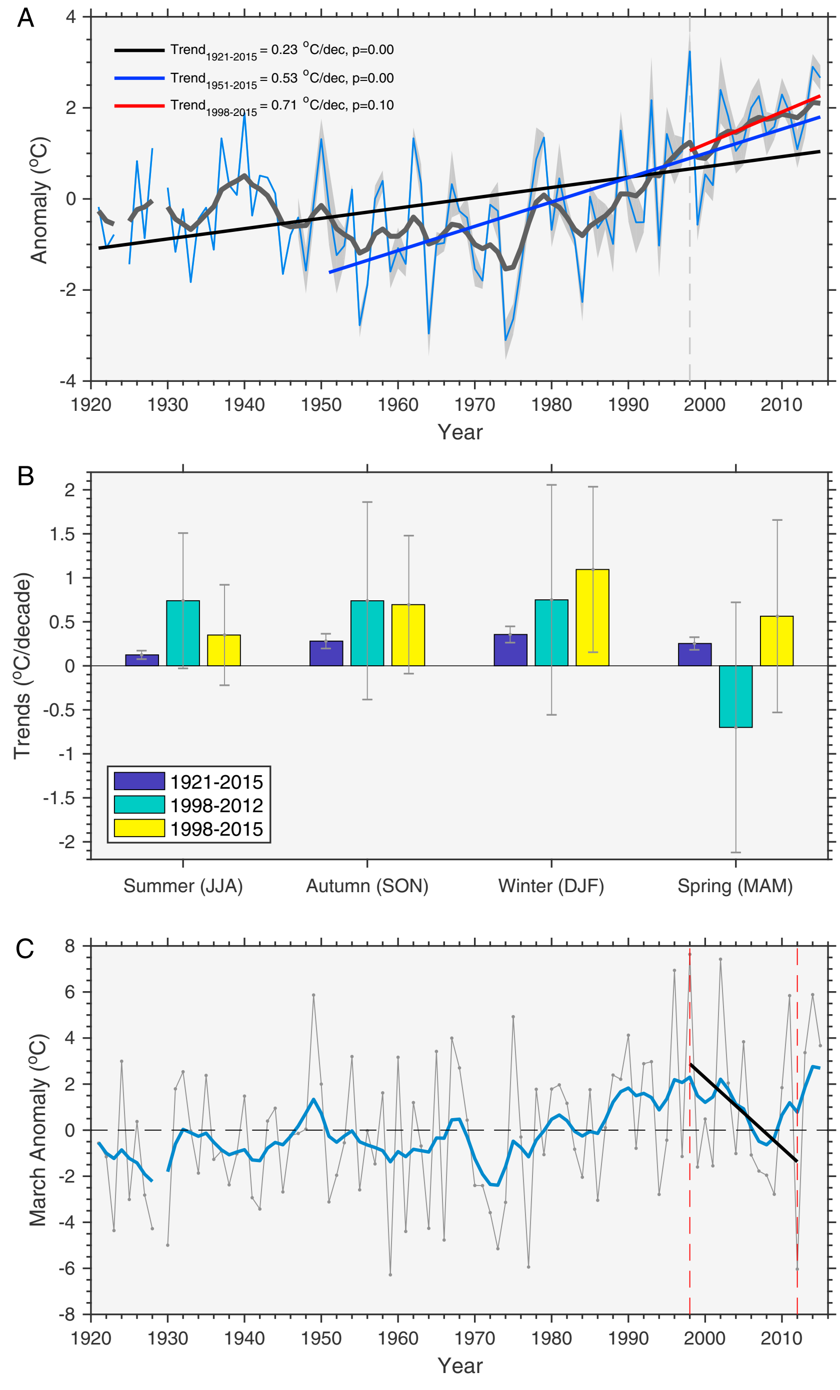

Figure 2. (a) MAAT anomalies for the Alaskan Arctic region (1921–2015). Blue line represents annual data points; gray shadows show the annual anomaly uncertainty of ±1 standard deviation; black curve is the smooth line using a low-pass filter with a cutoff frequency of 0.091 (approximately equivalent to an 11 year smoothing); the black, blue, and red lines are the linear trends for 1921–2015, 1951–2015, and 1998–2015, respectively. (b) Seasonal linear trends for 1921–2015, 1998–2012 (the defined hiatus period), and 1998–2015. Error bars represent the uncertainty (±1 standard deviation). (c) Changes in monthly mean air temperature during March 1921–2015. The black straight line is the trend during 1998–2012. Blue line is the smoothed MAAT using a low-pass filter with a cutoff frequency of 0.091 (approximately equivalent to an 11 year smoothing). Note that the temperature range of *y* axis is doubled compared to Figure 2a.

Table 1. Trends for Different Periods Using Available Data Sets[a]

Data Set	Period	Trend (°C/decade)	Uncertainty (°C/decade)	p Value
CRU		−0.09	0.94	0.87
BEST		−0.11	0.98	0.84
GISS	1998–2012	0.12	0.99	0.83
This study		0.45	1.02	0.45
CRU		0.21	0.66	0.58
BEST		0.35	0.73	0.42
GISS	1998–2015	0.25	0.71	0.55
This study		0.71	0.72	0.10
CRU		0.46	0.22	0.00
BEST		0.36	0.24	0.02
GISS	1976–2012	0.36	0.23	0.01
This study		0.74	0.26	0.00
CRU		0.49	0.19	0.00
BEST		0.43	0.21	0.00
GISS	1976–2015	0.37	0.20	0.00
This study		0.78	0.23	0.00
CRU		0.42	0.11	0.00
BEST		0.36	0.12	0.00
GISS	1951–2012	0.33	0.12	0.00
This study		0.50	0.14	0.00
CRU		0.44	0.10	0.00
BEST		0.39	0.11	0.00
GISS	1951–2015	0.34	0.11	0.00
This study		0.53	0.12	0.00
CRU		0.17	0.07	0.00
BEST		0.12	0.07	0.00
GISS	1921–2012	0.13	0.07	0.00
This study		0.19	0.08	0.00
CRU		0.19	0.06	0.00
BEST		0.15	0.07	0.00
GISS	1921–2015	0.14	0.07	0.00
This study		0.23	0.08	0.00

[a]Uncertainty and p value are based on 90% confidence level.

period 1998–2012. Meanwhile, the other three seasons showed consistent warming with a linear rate of 0.7°C/decade. The negative trend in spring significantly reduced the overall trend of MAAT for 1998–2012 (Figure 2b). Further analysis indicates that the strongest negative trend occurred during March (−0.3°C/decade, Figure 2c). In addition, the uncertainty of the trend estimation is large because the variability of climate in high-latitude regions is considerably stronger than other regions [*Serreze et al.*, 2000; *Polyakov and Johnson*, 2000]. Meanwhile, influence of the variability on trend estimation is magnified by the use of short time periods for the trend calculation [*Wilks*, 1995].

Since 1998, when the apparent warming hiatus started [*IPCC*, 2014], the Alaskan Arctic has experienced a strong warming with temperatures increasing 0.71°C/decade (Figure 2a). *IPCC* [2014] defines the magnitude of global mean temperature increase during the hiatus period at about half that of the warming magnitude since 1951. When examining the trends in the Alaskan Arctic, the magnitude of temperature increase was 0.53°C/decade from 1951 to 2015 (Figure 2a), which is actually 34% less than the magnitude from 1998 to 2015, the perceived hiatus period. This result demonstrates that there was no climate warming hiatus in the Alaskan Arctic.

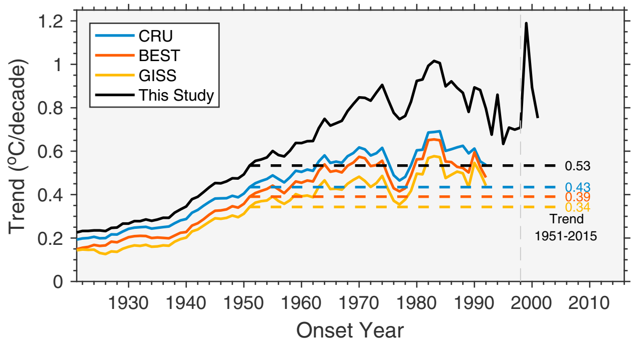

Figure 3. MAAT trends (°C/decade) in the Alaskan Arctic computed from the composite time series of anomalies according to CRU, BEST, GISS, and this study, ranging from 15 years (2001–2015) to the full record length (1921–2015), in 1 year increments. *X* axis is the onset year used to calculate the trend; the end of period is set to 2015. Horizontal colored dashed lines are corresponding trend values for 1951–2015. This figure shows only significant changes on 90% confidence level.

4. Discussion

Intergovernmental Panel on Climate Change (IPCC) diagnosed a hiatus period from 1998 to 2012 using CRU, BEST, and GISS data sets [*IPCC*, 2014]. We found that the trends in CRU, BEST, and GISS during the 1998–2012 are half of or even less than half of the trends for 1951–2012 (Table 1) in the Alaskan Arctic, which is consistent with the warming hiatus as defined by the *IPCC* [2014]. However, using a comprehensive data set established from the expanded in situ monitoring network, our results show an increase at 0.45°C/decade during 1998–2012 which is 90% of the warming rate for 1951–2012. Anomalies from the in situ data set since 1998 are generally higher than those in other studies by about 0.30–0.64°C. This is particularly true during the most recent decade (2006–2015) when the anomalies derived from the in situ data set are larger than other studies by 0.54–0.78°C. The differences are statistically significant at the 95% confidence level. The stronger anomalies during the recent decade enhanced the long-term trend. We also found a significant difference (0.33°C) between this study and *Bieniek et al.* [2014] which used fewer in situ observations.

We found that the differences in SAT anomaly increased with time. In order to investigate this potential effect on trend estimates, we calculated the trends using data from CRU, BEST, and GISS ranging from 15 years (2001–2015) to the full record length (1921–2015), in 1 year increments (Figure 3). CRU, BEST, and GISS data sets all show nonsignificant changes since 1993, while results from the in situ data set show a robust increasing trend (Figure 3). Meanwhile, the differences in the magnitude of temperature increase between the in situ data set and the other three data sets became larger with time (Figure 3). During 1921–2015, this study indicates temperatures increased 0.23°C/decade, while CRU, BEST, and GISS showed trends of 0.19, 0.15, and 0.14°C/decade, with differences of 0.04, 0.08, and 0.09°C/decade, respectively. However, the differences in the trends for 1976–2015 are 0.29, 0.35, and 0.41°C/decade, increased by 53%, 133%, and 193%, respectively. This shows that in situ data with better spatial coverage captures a continuous warming since the late 1990s and a further enhanced warming signal over the entire period.

The significant differences between the major gridded data sets and the new data set might be explained by the following reasons:

Incomplete observational coverage. Besides including the Berkeley Earth and GHCNv4 in situ stations which are mostly distributed along the Arctic coast, this study has added additional 17 stations evenly distributed across the Alaskan Arctic. By comparing the raw unhomogenized data from Berkeley Earth with the new data set from this study (31 stations), we found that the warming trend is 0.71°C/decade for 1998–2015, while the Berkeley Earth raw data set has a rate of 0.49°C/decade. We believe that the difference in the trend of 0.22°C/decade or 61% between these two data sets was produced by the number and spatial coverage of in situ stations in the study region.

We further divided the 31 stations used in this study into two groups: Group 1 consists of 14 stations which include all Berkeley Earth 12 raw stations and GHCNv4 10 raw data stations and Group 2 which includes the remaining 17 additional new stations. The trend for Group 2 is 0.76°C/decade, about 0.09°C/decade or 13% higher than the trend for Group 1 (Figure S2). This indicates that temperature increase was greater for the inland portion of the Alaskan Arctic than along the coast. Using data predominantly from the coastal areas may therefore be misleading.

Homogenization effect. Using the Berkeley Earth 12 station raw data sets and homogenized data sets, we conducted a trend analysis for 1998–2015. The trend for the raw data sets was 0.49°C/decade, while the trend for the homogenized data sets was 0.31°C/decade. Homogenization may result in spurious artifacts in regions with sparse station coverage and rapid, somewhat localized climate changes [*Cowtan and Way*, 2014b], and prior work has found that homogenized Berkeley Earth station data underestimate temperatures in high-latitude Arctic regions [*Way et al.*, 2017]. The homogenization produced a cooling bias of 0.18°C/decade when compared with the unhomogenized data sets (raw data sets). In detail, Berkeley Earth's homogenization algorithm made an adjustment of 0.6–0.8°C for Barrow MAAT records since the late 1990s (Figure S3). Similarly, in GHCNv3, the homogenization algorithm introduced a cooling bias of about 0.7°C for Barrow since 1990s while it did not make any changes for Bettles and Kotzebue (Figure S4). The cooling bias seems to be corrected in GHCNv4 (Figure S5), while they used the same homogenization method in GHCNv3. In fact, this is because the data processing group realized the incorrect adjustments in the region north of 65°N and skipped all stations in the high-latitude regions [*Lawrimore et al.*, 2016]. While this analysis cannot completely rule out the presence of localized inhomogeneities, the newly established 17 stations were never moved and the sensors either did not change or data have been corrected accordingly based on sensor calibration standards. The difference of trends between Group 1 (NWS stations) and Group 2 (new stations) was about 0.09°C/decade (Figure S2), suggesting that the NWS station raw data are reliable and the homogenization processes indeed produced cooling bias. This reinforces prior findings that the pairwise homogenization may be incomplete in treating the regions with sparse observational data.

The CRU data set only included Barrow, Cape Lisburne, and Barter Island in the study region (Figure S6a), while many sites within their correlation distance (1200 km) are mostly located in the interior Alaska, or even southern Alaska. The nearest sites are Bettles and Kotzebue, which are located south of the Brooks Range (Figure S6a). These stations showed changes in SAT of −0.29°C/decade in Bettles and 0.58°C/decade in Kotzebue from 1998 through 2015 (Figures S6b and S6c). In addition, we found a significant positive anomaly in 1998 in the Alaskan Arctic, while it did not occur in either Bettles or Kotzebue. Because the gridded data sets were created using the interpolation of anomalies on high-resolution climatology map [*Harris et al.*, 2014], air temperature changes at sites south of the Brooks Range certainly have a strong influence on overall gridded results across the Alaskan Arctic. However, climate controls over the high Arctic have changed dramatically due to the shifts of the Arctic/North Atlantic Oscillation centers during the recent decades [*Zhang et al.*, 2008], which caused the continued climate warming in Alaskan Arctic.

Uncertainty in spatial interpolation. Spatial interpolation is a useful tool for producing estimates in areas devoid of data. However, interpolation methods can introduce an obscure bias because of their specific algorithms. If the offset between the interpolated result and input station data is a constant, the offset does not affect trend analyses. However, the offsets were found to vary with time (Figure S7). This is probably because different available stations were used for interpolation during each time. Comparing the trends from BEST gridded data and their homogenized station data, we found the difference was about 0.04°C/decade. That means the influence of spatial interpolation was limited.

In short, the SAT warming rate was 0.71°C/decade as detected by using the newly established 31 station data set, while the SAT trend for the Berkeley Earth gridded data set was 0.35°C/decade for 1998–2015 over the Alaskan Arctic. The 0.36°C/decade underestimate of the Berkeley Earth gridded data set can be explained by 0.22°C/decade or 61% due to the incomplete observational coverage, 0.18°C/decade or 50% due to the homogenization effect, and −0.04°C/decade or −11% due to the spatial interpolation. Essentially, the biases by the homogenization effect and the spatial interpolation were also produced by the incomplete observational coverage [*Gubler et al.*, 2017]. This makes the incomplete observational measurements the key challenge issue for climate change studies.

We found a cooling trend for 1998–2012 in March (Figure 2c). This cooling trend could be attributed to the weakening of extratropical storm activity in this area. Extratropical storms are fundamental mechanisms for poleward transient heat and moisture transport and cloud formation/redistribution, increasing downward sensible heat flux and longwave radiation and, in turn, surface air temperature when solar radiation is week [*Vihma et al.*, 2016]. Climatologically, the count of storms reaches its minimum over the Arctic during late winter [*Zhang et al.*, 2004], favoring cooling of surface air temperature. A further analysis of multidecade storm activity using a high-resolution regional reanalysis data set [*Zhang et al.*, 2016] shows a decrease in both count and intensity of storms over the Pacific Arctic region during March (not shown). This weakened storm activity accordingly plays a contributing role in cooling surface air temperature. In fact, Atmospheric Radiation Measurement (ARM) station records showed a decrease in cloudiness in spring since 1998 [*Dong et al.*, 2010].

Air temperature was colder under clear-sky conditions than under cloudy sky conditions in the Arctic [*Zhang et al.*, 1996; *Stone and Belchansky*, 2005]. Statistically, air temperature decreased by ~0.7°C when the cloud cover fraction declined by 5% [*Stone and Belchansky*, 2005]. *Zhang et al.* [1996] found that changes in cloud condition could alter the onset date of snowmelt up to a month, suggesting impacts of cloudiness on surface energy budgets. Investigation on changes in storm activity is out of the scope of this study. Nevertheless, it would be related to Arctic climate change and Pacific Decadal Oscillation (PDO) phase shift. *Hartmann and Wendler* [2005] showed the shift of PDO from negative to positive phase in 1976 pushed the climatology of Alaska to a warmer stage until 1998. Our records also showed a positive correlation between air temperature and PDO in March during 1998–2012 (Pearson correlation was 0.51, $p \leq 0.05$; Figure S8). In addition, cloudiness would decrease with the decline of PDO [*Hartmann and Wendler*, 2005].

5. Conclusions

In contrast to the widely used global gridded data sets, our analysis demonstrates continued climate warming and no evidence for a climate warming hiatus during 1998–2015 over the Alaskan Arctic. Additional in situ data in the Alaskan Arctic provides improved spatial coverage and high confidence of capturing a true signal of climate change. The currently available gridded data sets such as CRU, BEST, and GISS included limited in situ observations for Arctic Alaska and may be "contaminated" by data from far away stations during the homogenization and spatial interpolation processes. We believe that there is a large bias in regional analysis using global gridded data sets in high-latitude or other regions with sparse observations. Underestimated Arctic warming from the gridded data sets provide biased information for Earth system modelers and policy makers. Although the Arctic is a small fraction of the global area, we still need to pay more attention to the amplified changes in this region because of its important amplification to climate system and contribution to the global assessment as well as potential feedback.

Results from this study imply that the SAT rise in recent decades may have been underestimated due to incomplete observational coverage in the Arctic and other poorly represented regions, contributing to the apparent warming hiatus. Underestimates of climate warming were also reported in Greenland [*Orsi et al.*, 2017] and northern Canada [*Way et al.*, 2017]. It is likely that enhanced climate warming may also have happened in the other regions of the Arctic since the late 1990s but left undetected because of incomplete observational coverage. Previous studies suggested that an observational density of one station per 3600 km^2 is adequate to capture 90% or more of temperature variability in simple terrain [*Hubbard*, 1994]. Consequently, there should be at least 60 stations over the Alaskan Arctic. Critically, in complex and high variability regions, twice the spatial density is needed to capture the regional climate signal [*Janis et al.*, 2004]. Thus, the NWS observational density in the Alaskan Arctic is extremely low and unable to trace climate variability. To continuously monitor global climate change and variability, it is a prerequisite that rationally distributed ground-based measurements be established and maintained worldwide, especially in the Arctic.

Acknowledgments
This study was supported by the National Natural Science Foundation of China (grant 91325202) and the National Basic Research Program of China (grant 2013CBA01802). K.W. and I.O. were supported by the National Science Foundation (award 1503559). X.Z. was supported by the National Science Foundation (award 1023592). G.C. was supported by the U.S. Geological Survey's Climate and Land Use Change Program. We thank the reviewers and Editor for their insightful comments and suggestions that lead to an improved version of the manuscript. We also thank all for producing and making their data available in the harsh environment. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. Processed data are available in the supporting information file (Data Set S1).

6. Data Availability

In situ air temperature data were obtained from multiple sources: (i) GHCN-Daily, https://www.ncdc.noaa.gov/oa/climate/ghcn-daily/; (ii) GSOD, ftp://ftp.ncdc.noaa.gov/pub/data/gsod/; (iii) USGS, http://pubs.usgs.gov/ds/0977/introduction.html (the entire observational network consists of 17 stations and deployed by 2007); (iv) UAF-GI, http://permafrost.gi.alaska.edu/sites_list; and (v) CALM, https://www2.gwu.edu/~calm/data/north.html. The gridded data sets were obtained from the CRU TS3.24 (https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_3.24/), BEST (http://berkeleyearth.lbl.gov/auto/Global/Gridded/CompleteTAVGLatLong1.nc), and GISS (https://data.giss.nasa.gov/pub/gistemp/gistemp250.nc.gz). The last visit date of all above data sets is 15 April 2016. All the statistics were implemented using MATLAB 2016b.

References

Bieniek, P. A., et al. (2012), Climate divisions for Alaska based on objective methods, *J. Appl. Meteorol. Climatol.*, *51*(7), 1276–1289, doi:10.1175/jamc-d-11-0168.1.

Bieniek, P. A., J. E. Walsh, R. L. Thoman, and U. S. Bhatt (2014), Using climate divisions to analyze variations and trends in Alaska temperature and precipitation, *J. Clim.*, *27*(8), 2800–2818, doi:10.1175/JCLI-D-13-00342.1.

Brown, J., K. Hinkel, and F. Nelson (2000), The Circumpolar Active Layer Monitoring (CALM) program: Research designs and initial results, *Pol. Geogr.*, *24*(3), 166–258.

Cohen, J., J. A. Screen, J. C. Furtado, M. Barlow, D. Whittleston, D. Coumou, J. Francis, K. Dethloff, D. Entekhabi, J. Overland, and J. Jones (2014), Recent Arctic amplification and extreme mid-latitude weather, *Nat. Geosci.*, *7*(9), 627–637.

Cowtan, K., and R. G. Way (2014a), Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends, *Q. J. R. Meteorol. Soc.*, *140*(683), 1935–1944, doi:10.1002/qj.2297.

Cowtan, K., and R. G. Way (2014b), Coverage Bias in the HadCRUT4 Temperature Series and Its Impact on Recent Temperature Trends - Reconciling global temperature series, Univ. of York, York, U. K. [Available at https://www-users.york.ac.uk/~kdc3/papers/coverage2013/update.140404.pdf, Accessed date: September 5, 2017.]

Dong, X., B. Xi, K. Crosby, C. N. Long, R. S. Stone, and M. D. Shupe (2010), A 10 year climatology of Arctic cloud fraction and radiative forcing at Barrow, Alaska, *J. Geophys. Res.*, *115*, D17212, doi:10.1029/2009JD013489.

Douville, H., A. Voldoire, and O. Geoffroy (2015), The recent global warming hiatus: What is the role of Pacific variability?, *Geophys. Res. Lett.*, *42*(3), 880–888, doi:10.1002/2014GL062775.

England, M. H., S. McGregor, P. Spence, G. A. Meehl, A. Timmermann, W. Cai, A. S. Gupta, M. J. McPhaden, A. Purich, and A. Santoso (2014), Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus, *Nat. Clim. Change*, *4*(3), 222–227, doi:10.1038/nclimate2106.

Fyfe, J. C., G. A. Meehl, M. H. England, M. E. Mann, B. D. Santer, G. M. Flato, E. Hawkins, N. P. Gillett, S.-P. Xie, Y. Kosaka, and N. C. Swart (2016), Making sense of the early-2000s warming slowdown, *Nat. Clim. Change*, *6*(3), 224–228, doi:10.1038/nclimate2938.

Gubler, S., S. Hunziker, M. Begert, M. Croci-Maspoli, T. Konzelmann, S. BrÃPnnimann, C. Schwierz, C. Oria, and G. Rosas (2017), The influence of station density on climate data homogenization, *Int. J. Climatol.*, doi:10.1002/joc.5114.

Hansen, J., R. Ruedy, M. Sato, and K. Lo (2010), Global surface temperature change, *Rev. Geophys.*, *48*, RG4004, doi:10.1029/2010RG000345.

Harris, I., P. Jones, T. Osborn, and D. Lister (2014), Updated high-resolution grids of monthly climatic observations-the CRU TS3.10 dataset, *Int. J. Climatol.*, *34*(3), 623–642.

Hartmann, B., and G. Wendler (2005), The significance of the 1976 Pacific climate shift in the climatology of Alaska, *J. Clim.*, *18*(22), 4824–4839, doi:10.1175/JCLI3532.1.

Hubbard, K. G. (1994), Spatial variability of daily weather variables in the high plains of the USA, *Agric. Forest Meteorol.*, *68*(1), 29–41, doi:10.1016/0168-1923(94)90067-1.

Huber, M., and R. Knutti (2014), Natural variability, radiative forcing and climate response in the recent hiatus reconciled, *Nat. Geosci.*, *7*(9), 651–656, doi:10.1038/ngeo2228.

Intergovernmental Panel on Climate Change (IPCC) (2014), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker et al., 1552 pp., Cambridge Univ. Press, Cambridge, U. K., and New York.

Janis, M. J., K. G. Hubbard, and K. T. Redmond (2004), Station density strategy for monitoring long-term climatic change in the Contiguous United States, *J. Clim.*, *17*(1), 151–162, doi:10.1175/1520-0442(2004)017<0151:sdsfml>2.0.co;2.

Karl, T. R., A. Arguez, B. Huang, J. H. Lawrimore, J. R. McMahon, M. J. Menne, T. C. Peterson, R. S. Vose, and H.-M. Zhang (2015), Possible artifacts of data biases in the recent global surface warming hiatus, *Science*, *348*(6242), 1469–1472, doi:10.1126/science.aaa5632.

Lawrimore, J., R. Vose, and J. Privette (2016), Algorithm theoretical basis document: GHCN-Monthly version 4 mean temperature (version 1.0), *Tech. Rep.*, Natl. Oceanic and Atmos. Admin., U.S. Dep. of Commerc., Asheville, N. C. [Available at: ftp://ftp.ncdc.noaa.gov/pub/data/ghcn/v4/documentation/ghcnm-v4-atbd-20161114.pdf, Accessed date: September 5, 2017.]

Medhaug, I., M. B. Stolpe, E. M. Fischer, and R. Knutti (2017), Reconciling controversies about the “global warming hiatus”, *Nature*, *545*(7652), 41–47, doi:10.1038/nature22315.

Meehl, G. A., H. Teng, and J. M. Arblaster (2014), Climate model simulations of the observed early-2000s hiatus of global warming, *Nat. Clim. Change*, *4*(10), 898–902.

Menne, M. J., I. Durre, R. S. Vose, B. E. Gleason, and T. G. Houston (2012), An overview of the Global Historical Climatology Network-Daily Database, *J. Atmos. Oceanic Technol.*, *29*(7), 897–910, doi:10.1175/jtech-d-11-00103.1.

Orsi, A. J., K. Kawamura, V. Masson-Delmotte, X. Fettweis, J. E. Box, D. Dahl-Jensen, G. D. Clow, A. Landais, and J. P. Severinghaus (2017), The recent warming trend in North Greenland, *Geophys. Res. Lett.*, *44*, 6235–6243, doi:10.1002/2016GL072212.

Polyakov, I. V., and M. A. Johnson (2000), Arctic decadal and interdecadal variability, *Geophys. Res. Lett.*, *27*(24), 4097–4100, doi:10.1029/2000GL011909.

Roberts, C. D., M. D. Palmer, D. McNeall, and M. Collins (2015), Quantifying the likelihood of a continued hiatus in global warming, *Nat. Clim. Change*, *5*(4), 337–342, doi:10.1038/nclimate2531.

Rohde, R., R. A. Muller, R. Jacobsen, E. Muller, S. Perlmutter, A. Rosenfeld, J. Wurtele, D. Groom, and C. Wickham (2012), A new estimate of the average earth surface land temperature spanning 1753 to 2011, *Geoinform. Geostat.*, *1*(1), 1–7, doi:10.4172/2327-4581.1000101.

Santer, B. D., C. Bonfils, J. F. Painter, M. D. Zelinka, C. Mears, S. Solomon, G. A. Schmidt, J. C. Fyfe, J. N. Cole, and L. Nazarenko (2014), Volcanic contribution to decadal changes in tropospheric temperature, *Nat. Geosci.*, *7*(3), 185–189.

Serreze, M. C., J. E. Walsh, F. S. Chapin, T. Osterkamp, M. Dyurgerov, V. Romanovsky, W. C. Oechel, J. Morison, T. Zhang, and R. G. Barry (2000), Observational evidence of recent change in the northern high-latitude environment, *Clim. Change*, *46*(1), 159–207, doi:10.1023/a:1005504031923.

Serreze, M. C., A. P. Barrett, J. C. Stroeve, D. N. Kindig, and M. M. Holland (2009), The emergence of surface-based Arctic amplification, *Cryosphere*, *3*(1), 11–19, doi:10.5194/tc-3-11-2009.

Stone, D., and D. Belchansky (2005), Correlated declines in Pacific arctic snow and sea ice cover, *Arctic Res. U.S.*, *19*(1), 18–25.

Trenberth, K. E., J. T. Fasullo, G. Branstator, and A. S. Phillips (2014), Seasonal aspects of the recent pause in surface warming, *Nat. Clim. Change*, *4*(10), 911–916, doi:10.1038/nclimate2341.

Urban, F. E., and G. D. Clow (2016), GTN-P climate and active-layer data acquired in the national petroleum reserve—Alaska and the Arctic national wildlife refuge, 1998–2014.

Vihma, T., J. Screen, M. Tjernström, B. Newton, X. Zhang, V. Popova, C. Deser, M. Holland, and T. Prowse (2016), The atmospheric role in the Arctic water cycle: A review on processes, past and future changes, and their impacts, *J. Geophys. Res. Biogeosci.*, *121*, 586–620, doi:10.1002/2015JG003132.

Walsh, J. E. (2014), Intensified warming of the Arctic: Causes and impacts on middle latitudes, *Global Planet. Change*, *117*, 52–63.

Way, R. G., F. Oliva, and A. E. Viau (2017), Underestimated warming of northern Canada in the Berkeley Earth temperature product, *Int. J. Climatol.*, *37*(4), 1746–1757, doi:10.1002/joc.4808.

Wilks, D. S. (1995), *Statistical Methods in the Atmospheric Sciences: An Introduction*, vol. 59, 467 pp., Academic Press, San Diego, Calif.

Zhang, J., F. Liu, W. Tao, J. Krieger, M. Shulski, and X. Zhang (2016), Mesoscale climatology and variation of surface winds over the Chukchi-Beaufort coastal areas, *J. Clim.*, *29*(8), 2721–2739, doi:10.1175/JCLI-D-15-0436.1.

10.1002/2017GL074232

Zhang, T., K. Stamnes, and S. A. Bowling (1996), Impact of clouds on surface radiative fluxes and snowmelt in the Arctic and Subarctic, *J. Clim.*, *9*(9), 2110–2123, doi:10.1175/1520-0442(1996)009<2110:IOCOSR>2.0.CO;2.

Zhang, X., J. E. Walsh, J. Zhang, U. S. Bhatt, and M. Ikeda (2004), Climatology and interannual variability of Arctic cyclone activity: 1948–2002, *J. Clim.*, *17*(12), 2300–2317, doi:10.1175/1520-0442(2004)017<2300:CAIVOA>2.0.CO;2.

Zhang, X., A. Sorteberg, J. Zhang, R. Gerdes, and J. C. Comiso (2008), Recent radical shifts of atmospheric circulations and rapid changes in Arctic climate system, *Geophys. Res. Lett.*, *35*, L22701, doi:10.1029/2008GL035607.